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G11B 5/55

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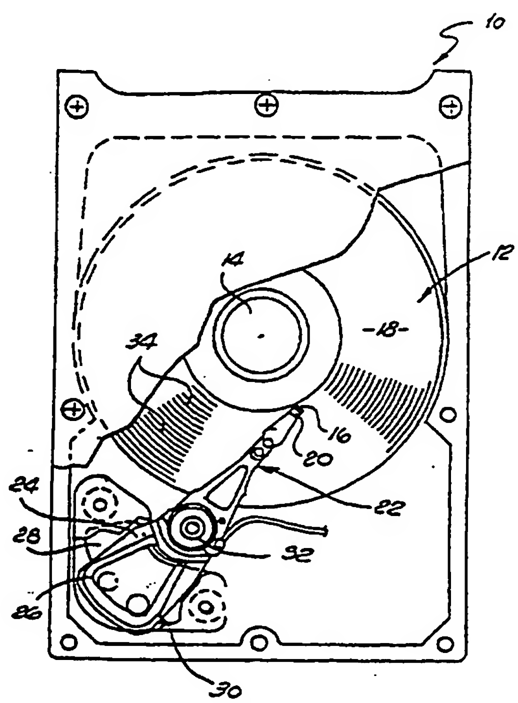
(54) Abstract Title
Low noise hard disc drive

(57) A hard disc drive (10) is described in which movement of a transducer (16) on an actuator arm (24) across the surface of a disc (12) is controlled so that the acceleration of the read/write transducer is a substantially sinusoidal function of time. The transducer is integrated into a slider (20) that is incorporated into a head gimbal assembly (22). The movement of the actuator arm and the transducer is controlled by a controller that moves the transducer from a first track to a new track in accordance with a seek routine and a servo control routine. The sinusoidal acceleration reduces the high harmonics found in conventional square waveforms, and thus minimises the acoustic noise of the head gimbal assembly and reduces the settling time of the transducer and the duration of the seek routine. Also described is the generation of position, velocity and acceleration values on the basis of actual and ideal position, velocity and acceleration respectively.



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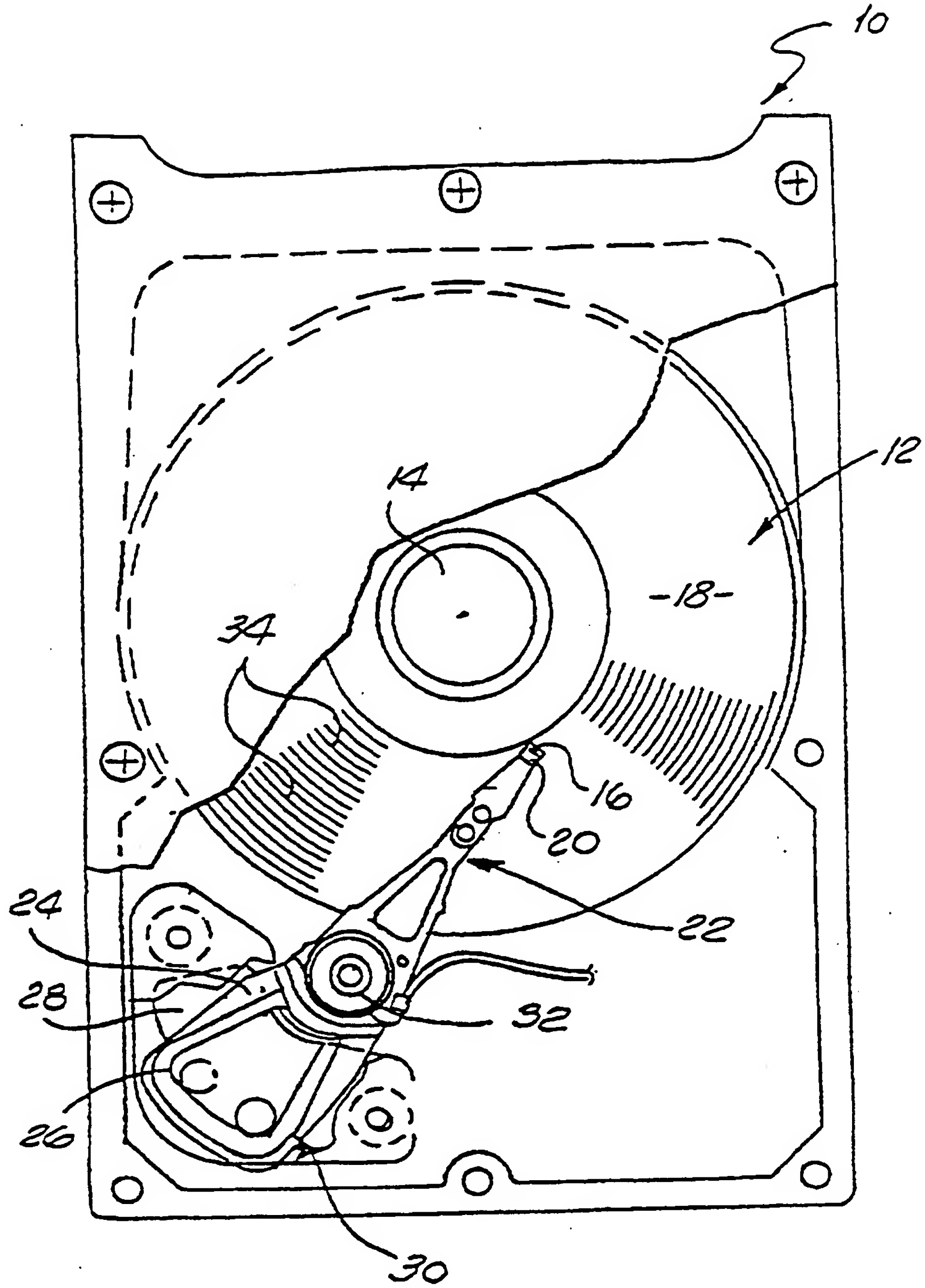
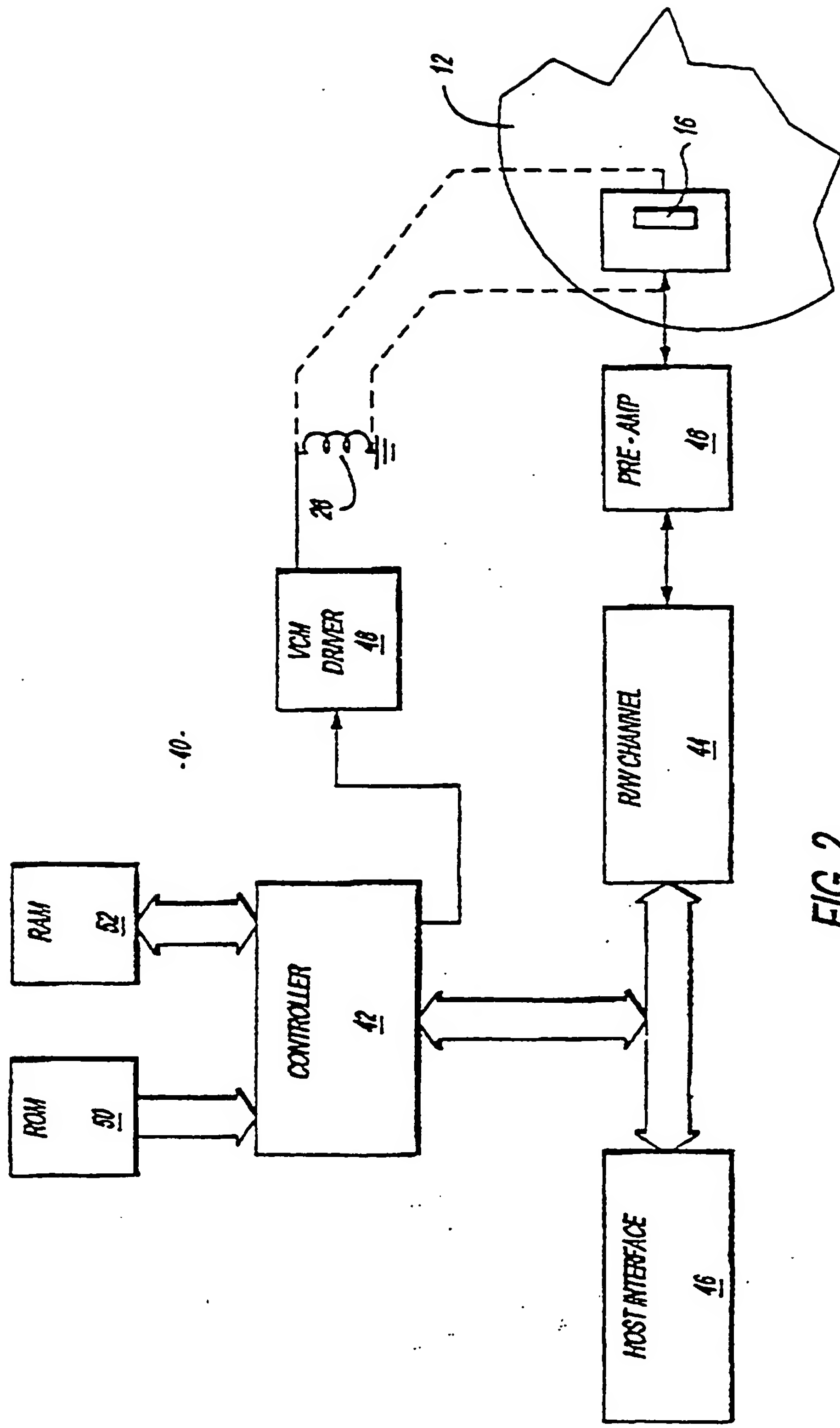
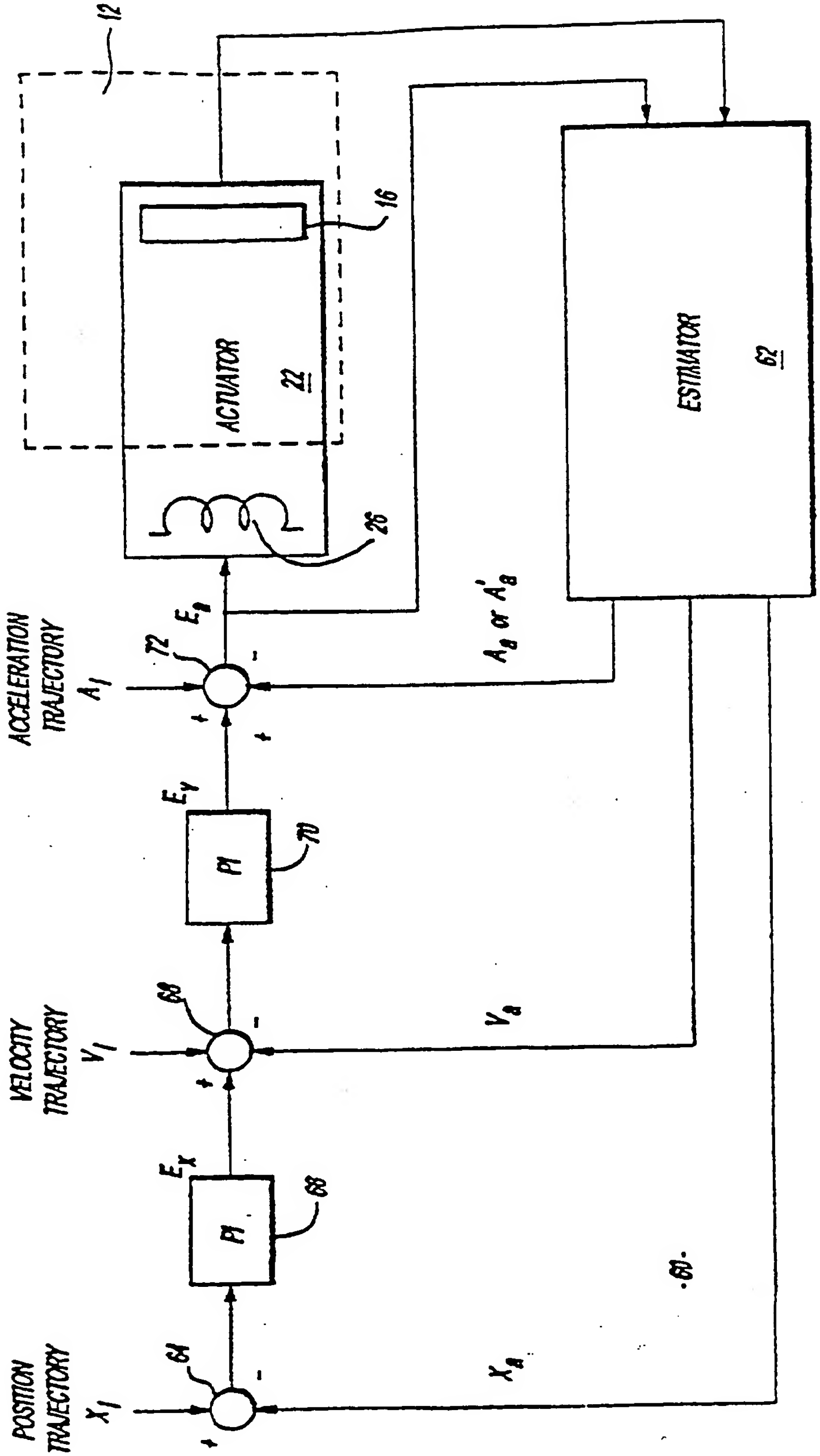


FIG. 1



12
16
20
VCM DRIVER 48
PRE-AMP 48
40
RAM 52
ROM 50
CONTROLLER 42
R/W CHANNEL 44
HOST INTERFACE 46

FIG. 2


POSITION TRAJECTORY X_I
VELOCITY TRAJECTORY V_I
ACCELERATION TRAJECTORY A_I
E_X
E_V
E_B
PI
PI
ACTUATOR
22
ESTIMATOR
62
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16
26
64
66
68
70
72
60
X_B
V_B
A_B or A'_B

FIG. 3

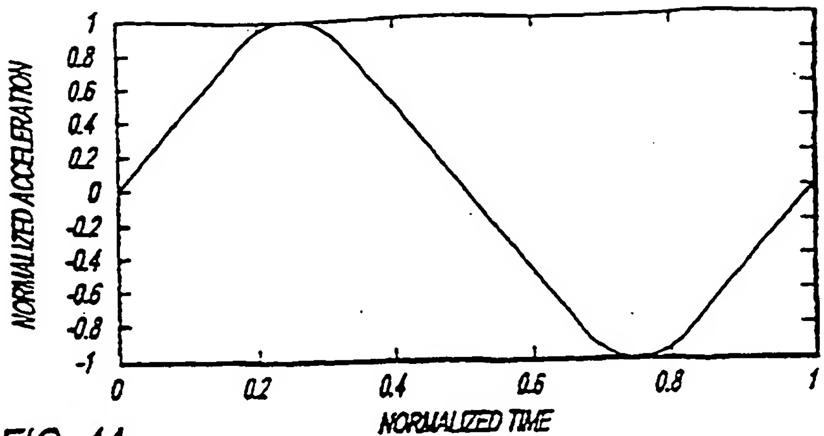

FIG. 4A

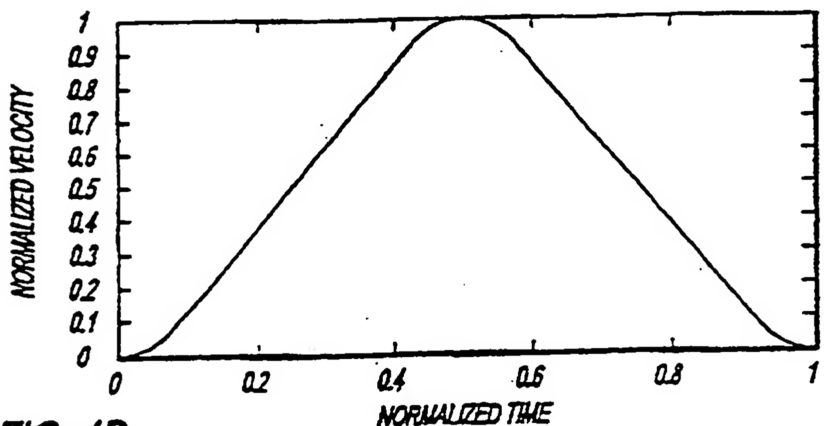

FIG. 4B

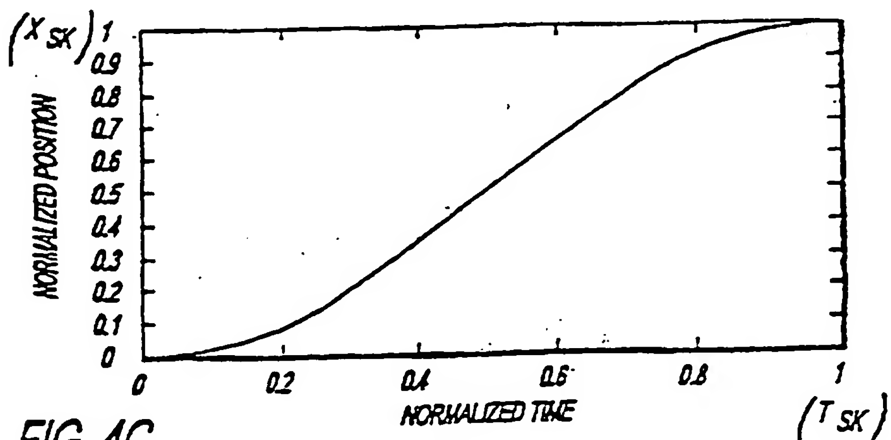

FIG. 4C

LOW NOISE HARD DISK DRIVE

BACKGROUND TO THE INVENTION

The present invention relates generally to firmware associated with a hard disk drive and more particularly to a method and apparatus for reducing the acoustic noise generated by movements of data read/write componentry of a hard disk drive assembly, to reduce settling time and provide accurate head positioning.

Hard disk drive include a plurality of magnetic transducers that can write and read information by magnetising and sensing the magnetic field of a rotating disk. The information is typically formatted into a plurality of sectors that are located within an annular track. There are a number of tracks located across each surface of the disk. A number of vertically similar tracks are sometimes referred to as a cylinder. Each track may therefore be identified by a cylinder number.

Each transducer is typically integrated into a slider that is incorporated into a head gimbal assembly (HGA). Each HGA is attached to an actuator arm. The actuator arm has a voice coil located adjacent to a magnet assembly which together define a voice coil motor. The hard disk drive typically includes a driver circuit and a controller that provide current to excite the voice coil motor. The excited voice coil motor rotates the actuator arm and moves the transducers across the surfaces of the disk(s).

When writing or reading information the hard disk drive may perform a seek routine to move the transducers from one cylinder (track) to another cylinder. During the seek routine the void coil motor is excited with a current to move the transducers to the new cylinder location on the disk surfaces. The controller also performs a servo routine to ensure that the transducer moves to the correct cylinder location.

Many disk drives utilise a "bang-bang" control loop for the servo routine to ensure that the transducer is moved to the correct location. The shape of the current waveform for seek routines that utilise bang-bang control theory is typically square.

Unfortunately, square waveforms contain high frequency harmonics which stimulate mechanical resonance in the HGA causing acoustic noise.

It is always desirable to minimise the amount of time required to write and read information from the disk or disks. Therefore, the seek routine performed by the drive should move the transducers to the new cylinder location in the shortest amount of time. Additionally, the settling time of the HGA should be minimised so that the transducer can quickly write or read information, once located adjacent to the new cylinder.

The mechanical resonance created by the square waveforms of the prior art tend to increase both the settling and

overall time required to write or read information from the disk. It would therefore be desirable to provide a seek routine that minimises the mechanical resonance of the HGA, thereby decreasing acoustic noise and reducing settling time.

SUMMARY OF THE INVENTION

A hard disk drive according to the present invention comprises a rotating data storage disk, a transducer that is movable across the surface of the disk to write information onto the disk and read information from it and means for controlling the movement of the transducer so that its acceleration across the surface of the disk is a substantially sinusoidal function of time.

The present invention also encompasses, in a hard disk drive comprising a rotating data storage disk and a transducer that is movable across the surface of the disk to write information onto the disk and read information from it, a method of controlling the movement of the transducer so that its acceleration across the surface of the disk is a substantially sinusoidal function of time.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will now be described by way of example with reference to the accompanying drawings in which:

Figure 1 is a top view of a hard disk drive of the present invention;

Figure 2 is a schematic of an electrical system which controls the hard disk drive;

Figure 3 is a schematic of a servo control system of the disk drive;

Figures 4a-c are graphs which show acceleration, velocity and position of a transducer of the disk drive.

DETAILED DESCRIPTION

The present invention provides a hard disk drive which moves a transducer across a disk surface so that the transducer has an essentially sinusoidal acceleration trajectory. The transducer may be integrated into a slider that is incorporated into a head gimbal assembly (HGA). The head gimbal assembly may be mounted to an actuator arm which can move the transducer across the disk surface. The movement of the actuator arm and the transducer may be controlled by a controller. The controller may move the transducer from a present track to a new track in accordance with a seek routine and a servo control routine.

During the seek routine the controller may move the transducer in accordance with a sinusoidal acceleration trajectory. The sinusoidal trajectory may reduce the high harmonics found in square waveforms of the prior art, and minimise the mechanical resonance and thus the acoustic noise of the head gimbal assembly. Reducing the acoustic noise of the HGA may reduce the settling time of the transducer for reducing the duration of the seek routine. Reducing the acoustic noise may also provide accurate positioning of the transducer relative to a desired track of the disk.

Referring to the drawings move particularly by reference numbers, Figure 1 shows an embodiment of a hard disk drive 10. The drive 10 includes at least one magnetic disk 12 that is rotated by a spin motor 14. The drive 10 may also include a transducer 16 located adjacent to a disk surface 18.

The transducer 16 can write and read information on the rotating disk 12 by magnetising and sensing the magnetic field of the disk 12, respectively. There is typically a transducer 16 associated with each disk surface 18. Although a single transducer 16 is shown and described, it is to be understood that there may be a write transducer for magnetising the disk 12 and a separate read transducer for sensing the magnetic field of the disk 12. The read transducer may be construed from a magneto-resistive (MR) material.

The transducer 16 can be integrated into a slider 20. The slider 20 may be constructed to create an air bearing between the transducer 16 and the disk surface 18. The slider 20 may be incorporated into a head gimbal assembly (HGA) 22. The HGA 22 may be attached to an actuator arm 24 which has a voice coil 26. The voice coil 26 may be located adjacent to a magnet assembly 28 to define a voice coil motor (VCM) 30. Providing a current to the voice coil 26 will generate a torque that rotates the actuator arm 24 about a bearing assembly 32. Rotation of the actuator arm 24 will move the transducer 16 across the disk surface 18.

Information is typically stored within annular tracks 34 of the disk 12. Each track 34 typically contains a plurality of sectors. Each sector may include a data field and an identification field. The identification field may contain grey code information which identifies the sector and track (cylinder). The transducer 16 is moved across the disk surface 18 to write or read information on a different track. Moving the transducer to access a different track is commonly referred to as a seek routine.

Figure 2 shows an electrical system 40 which can control the hard disk drive 10. The system 40 may include a controller 42 that is coupled to the transducer 16 by a read/write (R/W) channel circuit 44 and a pre-amplifier circuit 46. The controller 42 may be a digital signal processor (DSP). The controller 42 can provide control signals to the read/write channel 44 to read from the disk 12 or write information to the disk 12. The information is typically transferred from the R/W channel 44 to a host interface circuit 46. The host circuit 46 may include buffer memory and control circuitry which allow the disk drive to interface with a system such as a personal computer.

The controller 42 may also be coupled to a VCM driver circuit 48 which provides a driving current to the voice coil 26. The controller 42 may provide control signals to the driver circuit 48 to control the excitation of the VCM and the movement of the transducer 16.

The controller 42 may be connected to a read only memory (ROM) device 50 and a random access memory (RAM) device 52. The memory devices 50 and 52 may contain instructions and data that are used by the controller 42 to perform software routines. One of the software routines may be a seek routine to move the transducer 16 from one tract to another track. The seek routine may include a servo control routine to ensure that the transducer 16 moves to the correct track.

Figure 3 shows a servo control system 60 that is implemented by the controller 42. The servo control system 60 ensures that the transducer 16 is accurately located on a desired track of the disk 12. When the controller performs a seek routine the transducer 16 is moved from a first track to a new track located a distance X_{SK} from the first track. The grey codes of the tracks located between the new and first tracks are read as the transducer 16 moves across the disk 16. This, allows the controller to periodically determine whether the transducer 16 is moving at a desired speed or acceleration, or both, across the disk surface.

The control system 60 includes an estimator 62 that can determine the actual distance of position X_a that the transducer has moved from the first track. The position can be determined by reading the grey code of a track beneath the transducer 16. The estimator 62 can also determine the actual velocity V_a and the actual acceleration A_a of the transducer 16. The grey codes can be periodically sampled as the transducer 16 moves to the

new track location so that the controller can correct the movement of the transducer 16 with the servo control 60.

The controller 42 computes an ideal position X_i, and ideal velocity V_i and an ideal acceleration A_i of the transducer 16 each time the transducer reads the grey code of a track 34. The controller computes the difference between the ideal position X_i and the actual position X_a at summing junction 64. In block 66 the controller then computes a position correction value E_v with a proportional plus integral control algorithm and the output of the summing junction 64.

The actual velocity V_i is subtracted from the sum of the ideal velocity A_i and the position correction value E_p at summing junction 68. In block 70 the controller computes a velocity correction value E_v with a proportional plus integral control algorithm and the output of the summing junction 68.

An acceleration correction value E_a is computed by subtracting the actual acceleration A_a from the sum of the ideal acceleration A_i and the velocity correction value E_v at summing junction 72. The acceleration correction value A_a is used to increase or decrease the current provided to the voice coil 26 and to vary the acceleration of the movement of the transducer 16.

The acceleration correction value E_a may also be provided to the estimator 62 to generate a feedforward acceleration value A_a. The feedforward acceleration value

A_a can be provided to summing junction 72 to provide a feedforward control loop.

The ideal acceleration provided at the summing junction 72 preferably corresponds to the sinusoidal waveform shown in figure 4a. The corresponding ideal velocity and position waveforms are shown in Figures 4b and 4c, respectively. The sinusoidal waveform may be defined by the following equation:

$$a(t) = K_A I_M \sin\left(\frac{2\pi}{T_{SK}} t\right) \quad (1)$$

where:

K_A = acceleration constant;

I_m = maximum current provided to the voice coil;

T_{SK} = seek time required to move the transducer from the old track to the new track;

The following ideal velocity equation can be derived by integrating the acceleration equation.

$$v(t) = \int_0 a(t)dt = K_A I_M \frac{T_{SK}}{2\pi}\left[1 - \cos\left(\frac{2\pi}{T_{SK}} t\right)\right] \quad (2)$$

The following ideal position equation can be derived by integrating the velocity equation.

$$x(t) = \int_0 v(t)dt = K_A I_M \frac{T_{SK}}{2\pi}\left[t - \frac{T_{SK}}{2\pi}\sin\left(\frac{2\pi}{T_{SK}} t\right)\right] \quad (3)$$

When the disk drive is in operation, the disk drive may receive a command to store or read information. The command may require that the transducer be moved from a

first track to a new track in accordance with a seek routine. During a seek routine the new track and corresponding distance (seek length X_{sk}) to the new track from the first track can be determined by the controller. The seek time may be initially computed before the ideal acceleration, ideal velocity and ideal position are computed. The following relationship between T_{SK} and X_{SK} can be generated from equation (3) by setting $t=T_{SK}$.

$$T_{SK} = \sqrt{\frac{2\pi X_{SK}}{K_A I_M}} \tag{4}$$

Instead of performing a square root operation, the controller can compute T_{SK} from X_{SK} by generating a number of sample points N between $t=0$ and $t=T_{SK}$ and using the following linear interpolation algorithm to determine the seek time between sample points.

$$T_{SK} = T_{SK}^{I} + \frac{T_{SK}^{I+1} - T_{SK}^{I}}{X_{SK}^{I+1} - X_{SK}^{I}}\left(X_{SK} - X_{SK}^{I}\right) \tag{5}$$

During the servo routine the system may take a number of samples which correlate to the different positions, velocities, and accelerations of the transducer as the transducer moves from one track to another track. It is desirable to discretize the ideal trajectories to correspond with the sampling of grey codes so that the actual values can be subtracted from the ideal values at the summing junctions of the servo control shown in Fig. 3. To discretize the trajectories, equations (1), (2) and (3) are transformed into a sample domain (n) and equation (4) is substituted into the amplitude terms to generate the following equations.

$$a(n) = \frac{2\pi X_{SK}}{N_{SK}^2 T_{SM}^2} \sin\left(\frac{2\pi}{N_{SK}} n\right) \tag{6}$$

$$v(n) = \frac{X_{SK}}{N_{SK} T_{SM}} \left[1 - \cos\left(\frac{2\pi}{N_{SK}} n\right)\right] \tag{7}$$

$$x(n) = \frac{X_{SK}}{N_{SK}} n - \frac{X_{SK}}{2\pi} \sin\left(\frac{2\pi}{N_{SK}} n\right) \tag{8}$$

where:

T_{SM} = the sampling time, computed from equation (5);

N_{SK} = the total number of samples;

n = sample number

The sine and cosine values can be computed by utilising look-up tables that are stored in memory.

Alternatively, the sine and cosine values can be computed with the state equation and initial value of the following recursive sine wave generation algorithm.

$$\begin{bmatrix} x_c(n+1) \\ x_s(n+1) \end{bmatrix} = \begin{bmatrix} \cos\left(\frac{2\pi}{N_{SK}}\right) & -\sin\left(\frac{2\pi}{N_{SK}}\right) \\ \sin\left(\frac{2\pi}{N_{SK}}\right) & \cos\left(\frac{2\pi}{N_{SK}}\right) \end{bmatrix} \begin{bmatrix} x_c(n) \\ x_s(n) \end{bmatrix} \begin{bmatrix} x_c(0) \\ x_s(0) \end{bmatrix} = \begin{bmatrix} M \\ 0 \end{bmatrix} \tag{9}$$

which utilises the following known trigonometric identities.

$$\cos\left(\frac{2\pi}{N_{SK}}(n+1)\right) = \cos\left(\frac{2\pi}{N_{SK}}\right) \cos\left(\frac{2\pi}{N_{SK}} n\right) - \sin\left(\frac{2\pi}{N_{SK}}\right) \sin\left(\frac{2\pi}{N_{SK}} n\right) \tag{10}$$

$$\sin\left(\frac{2\pi}{N_{SK}}(n+1)\right) = \sin\left(\frac{2\pi}{N_{SK}}\right) \cos\left(\frac{2\pi}{N_{SK}} n\right) - \cos\left(\frac{2\pi}{N_{SK}}\right) \sin\left(\frac{2\pi}{N_{SK}} n\right) \tag{11}$$

During the servo routine the controller computes the ideal position, ideal velocity and ideal acceleration of

the transducer at a first sample time, determines the actual position, velocity and acceleration values and then processes the data in accordance with the control loop shown in Fig. 3 and described above. Second, third, etc. samples are taken and the process is repeated to provide a servo routine that controls the movement of the transducer.

The velocity of the transducer should not exceed a maximum value so that the transducer can accurately read grey codes from the disk. From equation (2) the maximum velocity can be computed as follows:

$$V_{MAX} = K_A I_M \frac{T_{SK}}{\pi} \tag{12}$$

Using equation (4) the maximum seek time and maximum seek length can be determined as follows.

$$T_{SK}^{M} = \frac{\pi}{K_A I_M} V_{MAX} \tag{13}$$

$$X_{SK}^{M} = \frac{\pi}{2K_A I_M} V_{MAX}^{2} \tag{14}$$

When the seek length X_{SK} exceeds the maximum seek length X_{SK}^{M}, a coast period must be introduced where the acceleration of the transducer is zero, so that the transducer velocity does not exceed the maximum value. The coast time can be defined by the following equation.

$$T_{CST} = \frac{X_{SK} - X_{SK}^{M}}{V_{MAX}} \tag{15}$$

For a seek length greater than X_{SK}^{M} the ideal position, ideal velocity and ideal acceleration trajectories may be defined in (n) domain by the following equations.

$$a(n) = \frac{2\pi 2X_{ACC}}{N_{SK}^{M^2} T_{SM}^{1}} \sin\left(\frac{2\pi}{N_{SK}^{M}} n\right) \qquad (16)$$

$$v(n) = \frac{2X_{ACC}}{N_{SK}^{M} T_{SM}} \left[1 - \cos\left(\frac{2\pi}{N_{SK}^{M}} n\right)\right] \qquad (17)$$

$$x(n) = \frac{2X_{ACC}}{N_{SK}^{M}} n - \frac{2X_{ACC}}{2\pi} \sin\left(\frac{2\pi}{N_{SK}^{M}} n\right) \qquad (18)$$

when the transducer is accelerating;

$$a(n) = 0 \qquad (19)$$

$$V(n) = V_{MAX} \qquad (20)$$

$$x(n) = X_{ACC} + V_{MAX} T_{SM} \left(n - N_{SK}^{M}/2\right) \qquad (21)$$

when the transducer is coasting;

$$a(n) = \frac{2\pi 2X_{DEC}}{N_{SK}^{M^2} T_{SM}^{2}} \sin\left(\frac{2\pi}{N_{SK}^{M}} \left(n - N_{CST}\right)\right) \qquad (22)$$

$$v(n) = \frac{2X_{DEC}}{N_{SK}^{M} T_{SM}} \left[1 - \cos\left(\frac{2\pi}{N_{SK}^{M}} \left(n - N_{CST}\right)\right)\right] \qquad (23)$$

$$x(n) = X_{ACC} + X_{CST} + \frac{2X_{DEC}}{N_{SK}^{M}} \left(n - N_{CST} - N_{SK}^{M}/2\right) - \frac{2X_{DEC}}{2\pi} \sin\left(\frac{2\pi}{N_{SK}^{M}} \left(n - N_{CST}\right)\right) \qquad (24)$$

when the transducer is decelerating;

where:

$X_{CST} = T_{CST} V_{MAX} for T_{CST}$ at coast phase, (25)

$X_{ACC} = \left(X_{SK} - X_{CST}\right)/2$ for $T_{SK}^{M}/2$ at acceleration phase, (26)

$X_{DEC} = X_{SK} - X_{ACC} - X_{CST}$ for $T_{SK}^{M}/2$ at deceleration phase, (27)

When the seek length exceeds X_{SK}^{M} the controller computes the ideal position, ideal velocity and ideal acceleration in accordance with equations (15) through (27), and then utilises the ideal values in the control loop Fig. 3.

The present invention provides a seek routine wherein the transducer is moved in an essentially sinusoidal acceleration trajectory and a servo control loop that corrects the input current so that the transducer moves in a desired path.

CLAIMS

1. A hard disk drive comprising:

a rotating data storage disk;

a transducer that is movable across the surface of the disk to write information onto the disk and read information from it; and

means for controlling the movement of the transducer so that its acceleration across the surface of the disk is a substantially sinusoidal function of time.

2. A hard disk drive according to claim 1 in which the disk is rotated by a spin motor.

3. A hard disk drive according to claim 1 or claim 2 in which the transducer is moved across the surface of the disk by an actuator arm that is controlled by the controller.

4. A hard disk drive according to any preceding claim in which the controller is a digital signal processor.

5. A hard disk drive according to claim 4 in which the digital signal processor controls the movement of the transducer in accordance with a linear interpolation algorithm.

6. A hard disk drive according to any preceding claim in which the controller is adapted to perform a servo routine that includes:

determining the actual position of the transducer;

computing an ideal position of the transducer;

generating a position correction value that is a function of the actual and ideal positions; and

varying the movement of the transducer using the position correction value.

7. A hard disk drive according to claim 6 in which the servo routine further includes:

determining the actual velocity of the transducer;

computing an ideal velocity of the transducer;

generating a velocity correction value that is a function of the position correction value and the actual and ideal velocities; and

varying the movement of the transducer using the velocity correction value.

8. A hard disk drive according to claim 7 in which the servo routine further includes:

determining the actual acceleration of the transducer;

computing an ideal acceleration of the transducer;

generating an acceleration correction value that is a function of the velocity correction value and the actual and ideal accelerations; and

varying the movement of the transducer using the acceleration correction value.

9. A hard disk drive according to claim 8 in which the acceleration correction value is also a function of a feedforward acceleration value provided in a feedforward control loop.

10. A hard disk drive according to claim 8 or claim 9 in which the controller is adapted to compute the ideal position, the ideal velocity and the ideal acceleration from a recursive sine wave generation algorithm.

11. A hard disk drive according to any one of claims 6-10 in which the controller is adapted to generate the position correction value from a proportional plus integral control algorithm.

12. A hard disk drive according to any one of claims 7-11 in which the controller is adapted to generate the velocity correction value from a proportional plus integral control algorithm.

13. A hard disk drive according to any preceding claim in which the substantially sinusoidal function of time includes a period during which it is substantially zero.

14. In a hard disk drive comprising a rotating data storage disk and a transducer that is movable across the surface of the disk to write information onto the disk and read information from it, a method of controlling the movement of the transducer so that its acceleration across the surface of the disk is a substantially sinusoidal function of time.

15. A method according to claim 14 in which the transducer is moved by exciting an actuator arm to which it is coupled.

16. A method according to claim 14 or claim 15, comprising:

computing an ideal position of the transducer;

determining the actual position of the transducer;

computing a position correction value from the ideal and actual positions; and

varying the movement of the transducer using the position correction value.

17. A method according to claim 16 in which the position correction value is computed from a proportional plus integral control algorithm.

18. A method according to claim 16 or claim 17, further comprising:

computing an ideal velocity of the transducer;

determining the actual velocity of the transducer;

computing a velocity correction value from the actual and ideal velocities and the position correction value; and

varying the movement of the transducer using the velocity correction value.

19. A method according to claim 18 in which the velocity correction value is computed from a proportional plus integral control algorithm.

20. A method according to claim 18 or claim 19, further comprising:

computing an ideal acceleration of the transducer;

determining the actual acceleration of the transducer;

computing an acceleration correction value from the actual and ideal accelerations and the velocity correction value; and

varying the movement of the transducer with the acceleration correction value.

21. A method according to claim 20 in which the acceleration correction value is a function of a feedforward acceleration value.

22. A method according to claim 20 or claim 21 in which the ideal acceleration, the ideal velocity and the ideal position are computed from a recursive sine wave generation algorithm.

23. A method according to claim 20 or claim 21 in which the ideal acceleration, the ideal velocity and the ideal position are computed from a linear interpolation algorithm.

24. A method according to any one of claims 14-23 in which the movement of the transducer includes a period during which the transducer undergoes substantially zero acceleration.

25. A hard disk drive substantially as described herein with reference to and/or as illustrated in the accompanying drawings.

26. A method of moving a transducer across a surface of a disk substantially as described herein with reference to the accompanying drawings

Application No:	GB 9923676.2	**Examiner:**	Rebecca Villis
Claims searched:	1-26	**Date of search:**	1 February 2000

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.R): G5R (RKA), (RKB), (RKC), (RKX)

Int Cl (Ed.7): G11B 5/55, 23/00

Other: Online: WPI, EPODOC, PAJ

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
Y	EP 0441407 A1	(FUJITSU)	7,18
X,Y	WO 93/09480 A1	(INTEGRAL PERIPHERALS)	X: 1,3-6,11,13-17 Y: 7,18

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.